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Introduction

A Working Group Meeting on Heavy Vehicle Aerodynamic Drag was held at Lawrence Livermore National Laboratory on August 16 - 17, 2000. The purpose of the meeting was to present technical details on the experimental and computational plans and approaches and provide an update on progress in the analysis of experimental results, model developments, simulations, and an investigation of an aerodynamic device. The focus of the meeting was a review of University of Southern California's (USC) experimental plans and results, NASA Ames experimental plans, the computational results from Lawrence Livermore National Laboratory (LLNL) and Sandia National Laboratories (SNL) for the integrated tractor-trailer benchmark geometry called the Ground Transportation System (GTS) Model, and turbulence model development and benchmark simulation for rounded cube shapes representative of a tractor and trailer being investigated by the California Institute of Technology (Caltech). Much of the meeting discussion involved wind tunnel testing plans, analysis of existing experimental data, simulation results, and needed modeling improvements. The present and projected budget and funding situation was also discussed.

Presentations were given by representatives from the Department of Energy (DOE) Office of Transportation Technology Office of Heavy Vehicle Technology (OHVT), LLNL, SNL, NASA Ames, USC, and Caltech. An industrial representative from International Truck and Engine Corporation participated in discussions and presented an industrial perspective. In addition, an overview of the laboratory was provided by an LLNL representative from their Engineering Directorate, and an update on the 21st Century Truck initiative was given by an LLNL representative from their Energy Directorate. This report contains the technical presentations (viewgraphs) delivered at the

August 2000 Working Group Meeting on Heavy Vehicle Aerodynamic Drag: Presentations and Summary of Comments and Conclusions

Jointly written by

Lawrence Livermore National Laboratory
Sandia National Laboratories
University of Southern California
California Institute of Technology
NASA Ames Research Center

Introduction

A Working Group Meeting on Heavy Vehicle Aerodynamic Drag was held at Lawrence Livermore National Laboratory on August 16 - 17, 2000. The purpose of the meeting was to present technical details on the experimental and computational plans and approaches and provide an update on progress in the analysis of experimental results, model developments, simulations, and an investigation of an aerodynamic device. The focus of the meeting was a review of University of Southern California's (USC) experimental plans and results, NASA Ames experimental plans, the computational results from Lawrence Livermore National Laboratory (LLNL) and Sandia National Laboratories (SNL) for the integrated tractor-trailer benchmark geometry called the Ground Transportation System (GTS) Model, and turbulence model development and benchmark simulation for rounded cube shapes representative of a tractor and trailer being investigated by the California Institute of Technology (Caltech). Much of the meeting discussion involved wind tunnel testing plans, analysis of existing experimental data, simulation results, and needed modeling improvements. The present and projected budget and funding situation was also discussed.

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Meeting, briefly summarizes the comments and conclusions, and outlines the future action items.

Summary of Major Issues

There were 3 major issues raised at the meeting.

1. With the projected funding for FY01, the desired experiments in the NASA 12' pressure wind tunnel (PWT) for the investigation of Reynolds number sensitivity can not be performed. Plans are to produce a multi-year plan to achieve this goal.

2. Another issue related to issue 1 is the choice of geometry for wind tunnel testing. The options are 1) Continue testing our Ground Transportation System (GTS), 2) Obtain a model from industry, or 3) Develop a generic model with a traditional vehicle shape, rather than the GTS cab over shape.

3. The team wishes to provide industry with our current status and results and to obtain feedback and guidance from industry as to the program experimental and computational plans. The desired approach is through an exchange of information during site visits and formal presentations at industry attended conferences.

Overview of the Project, Current Funding, and Other Activities

Jules Routbort of DOE OHVT and Argonne National Laboratory provided an overview of the OHVT budget for fiscal year (FY) 2000 and the projected budget for FY01 for heavy vehicle systems aerodynamic drag reduction. The OHVT call for proposals resulted in an additional $1.025 million being awarded to three companies for projects involving parasitic energy losses for heavy vehicle systems.

OHVT is also interested in providing funding for research and development related to heavy vehicle safety. Much of the meeting discussion focused on the safety issues of splash and spray. Experiments require moving ground planes and a computations would need to model of how a tire picks up water. It was mentioned that DOT has an ongoing project investigating methods for reducing splash and spray. (See related action items at end of report.)

An overview of the project was presented by Rose McCallen of LLNL. The viewgraphs are enclosed. Budget issues were presented as well as the project calendar of events and plans for submitting proposals for needed funding. Discussion at the end of the last meeting day with just the Aero team members resulted in a prioritized list of tasks and the deliverables expected with FY01 projected funding.

Industrial Perspective

Sunil Jain of International Truck and Engine Corporation provided an overview of the current aerodynamic effort at his company. It was emphasized that industry desires cost effective computational fluid dynamics (CFD) tools that they can use to improve the aerodynamics of their vehicles. The acquisition and use of these tools must be a minimum investment, otherwise experimentation will be more feasible. Industry's ultimate goal is to integrate CFD and wind tunnel testing and bring the computations into the design process. The importance of understanding the flow phenomena, determining optimum vehicle shape to minimize drag, and to be able to correlate the computed and experimental drag coefficient was discussed. Included in the presentation was a case where successful comparisons were made of calculations and experiments for a vehicle design with the use of a commercial CFD tool. It was suggested that the DOE Truck Aero Team provide industry with the CFD tools they are using so that they can investigate their use. It was also suggested that the Team establish collaborative relationships with the commercial software industry providing advanced modeling guidance that will enhance those tools now being used by the tractor manufacturers.

NASA's Plans for 7-ft x 10-ft Wind Tunnel Experiments in FY01 and Plans for 12-ft Wind Tunnel Experiments

Jim Ross of NASA Ames presented options for the 7-ft x 10-ft wind tunnel and 12-ft pressure wind tunnel tests which include experiments with a modified GTS model or use of a traditional vehicle (rather than a cab over shape like the GTS model) with more realistic features. NASA's plans also include provisions for USC to test their GTS model in the 7-ft x 10-ft wind tunnel for evaluation at lower blockage and higher Reynolds number flow. The purpose of all these experiments are for validation of the computational fluid dynamics (CFD) models and for further insight into truck flow phenomena. Details of the NASA test plans are provided in the attached viewgraphs. Several action items related to needed input from the Team on testing requirements are outlined in the action item list at the end of this report.

The public release of the NASA test data was also discussed. It is expected that by the end of October a NASA technical memo data report will be publicly released. The Team discussed the need for a special SAE conference session to release our computational and experimental analysis results.

USC's Wind Tunnel Tests and a Look at an Aero Device

Fred Browand of USC provided a detailed presentation of their gap flow and boattail analysis and a plan for future experiments and analysis of results. Also presented were plans for the development and testing of an oscillation device to control the trailer wake flow. The device alters the turbulent structure of the wake resulting in a drag reduction. Details of the analysis results and test plans are provided in the attached viewgraphs.

RANS and DES Computations at SNL

An overview of the Reynolds-averaged Navier Stokes (RANS) computation being performed by SNL was presented by Kambiz Salari. Current efforts involve the modeling of the NASA experiments in the 7-ft x 10-ft wind tunnel. The RANS calculation presented compare well with experiment except for the calculated pressure at the edges of the trailer base. It was recognized that accurate computation of the pressure gradient at the trailing edges of the trailer are important in correctly determining the vehicle drag. The possible need for edge effect corrections by averaging the pressures for the perpendicular element segments at the edge were discussed.

Some preliminary detached-eddy simulation (DES) results for flow around a circular cylinder were also presented. DES is a new turbulence modeling approach where RANS is used in wall regions and LES is used away from walls for reduced grid resolution requirements near walls. Details of the computations and analysis are provided in the attached viewgraphs.

Large-Eddy Simulations using the Finite Element Method at LLNL

The large-eddy simulation (LES) approach being used by LLNL was presented by Dan Flowers for both their compressible and incompressible flow models. The approach and development challenges were presented along with a progress update. Implementation of the incompressible model is complete and some validation remains. See attached viewgraphs for details on the models.

Jerry Owens of LLNL presented an overview of his research in the analysis of time dependent results with movies. Jerry's so called 'movie in the morning' approach for handling large and long running batch jobs, the resulting enormous computational data files, and quick production of movies of this data with overnight turn around was presented. The viewgraphs for this presentation are attached.

Greg Laskowski a student employee at LLNL from Stanford University presented his research and development in DES for incompressible flow modeling using the finite element method. Details are provided in the attached viewgraphs.

Simulations using Vortex Methods: A Gridless Technique

The Caltech group continues to improve their fast, parallelized, adaptive vortex method. Current activities at Caltech include: incorporating bodies with arbitrary complexity, obtaining higher Reynolds numbers computations, and developing and analyzing subgrid models for large-eddy simulation. Mark Brady of Caltech provided an update of their progress in the development and use of the vortex method approach for a two-body tractor-trailer geometry and Tony Leonard provided an overview of his investigation of wall

turbulence models. Simulation Reynolds numbers are still quite low but plans are to move into the higher Reynolds number regime with the addition of subgrid scale models. Details and results of computations with the vortex method code and on the turbulence modeling approach are in the attached viewgraphs.

Demonstration Vehicle

Ross Sheckler of Dynacs Corporation presented his preliminary design for a demonstration vehicle. Ross would like for the Team to choose his design for future testing in the NASA wind tunnels. The pros and cons of the various geometry options were discussed in addition to the possibilities of funding contributions from industry with the appropriate choice of model geometry. Requesting assistance from the Truck Manufacturing Association (TMA) in obtaining industry support was mentioned as a possible approach. Ross's viewgraphs are attached.

Action Items

The follow-on action items with the individuals responsible for the tasks are as follows:

Needed information for NASA experiments (K. Salari)

- Desired gap distance
- Inlet measurements desired (e.g., hot film, rake, PIV)
- Location of unsteady taps
- Are pressure sensitive paint measurements desired
- Determine if investigation of BLA Technology add-on desired.

Provide NASA with time estimate for USC experiments in 7-ft x10-ft wind tunnel (F. Browand)

Establish what model will use in FY01 and FY02 NASA tests (J. Ross)

Provide accuracy of measured C_p (J. Ross)

Complete team budget estimate for FY01 (R. McCallen)

Meeting report with viewgraphs (R. McCallen)

Quarterly report due November 15, 2000 (R. McCallen)

Establish location and schedule next working group meeting (R. McCallen)

Determine relation of splash and spray to vehicle accidents. Possible source of information is UPS. (R. Sheckler)

Gather information on the current R&D effort related splash and spray in DOT. (F. Browand)

Aerodynamic Drag Reduction for Class 2, 6, 7 & 8 Trucks

DOE's Aerodynamic Design of Heavy Vehicles Project Team

http://energy.llnl.gov/aerodrag

University of California
Lawrence Livermore National Laboratory

Sandia National Laboratories

USC UNIVERSITY OF SOUTHERN CALIFORNIA

Caltech
California Institute of Technology

National Aeronautics & Space Administration

Reducing aerodynamic drag has a higher potential leverage than any other technology improvement.

20 Year Projection

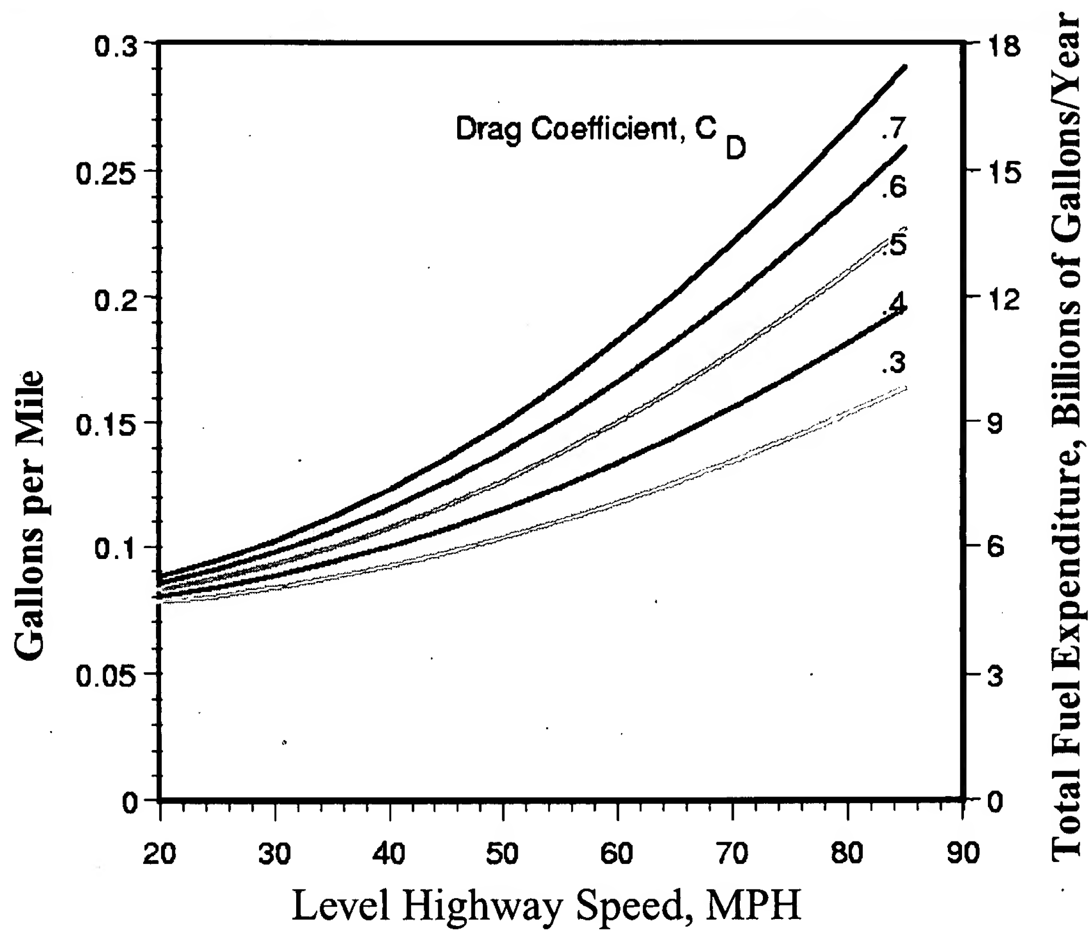
Technology	Fuel Reduction
Improve engine efficiency by 8%	8%
Weight Reduction of 15%	< 10%
Reduce aerodynamic drag by 25%	10 - 15%

Kenworth cab-over-engine (1990)

Kenworth T2000 conventional model (1999)

Impact on military versus commercial fuel consumption is dependent on vehicle duty cycles.

Class 8 tractor-trailer
C_D=0.6
speed > 60 mph

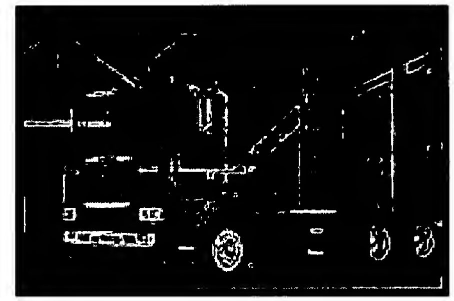


All vehicles will benefit from aerodynamic drag reductions – the higher the speed the higher the duration, the most benefit.

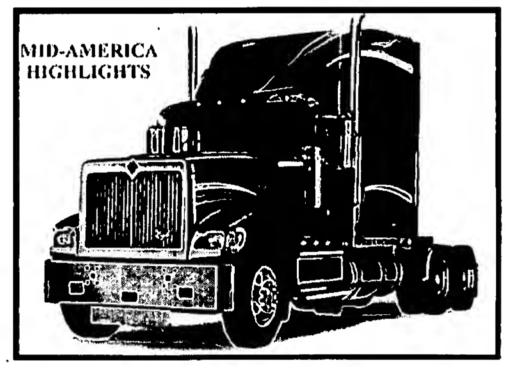
The truck industry relies on wind tunnel and field experiments for aerodynamic design and analysis.

Wind Tunnel Testing

- Costly detailed models
- Expensive tunnel use
- Trial-error approach to determine drag effects



Cabover Engine



Conventional

Field Testing

- Performed by both manufacturer and fleet operators

Issues

- A tractor is paired with several different trailers
- Almost no aero design interaction between tractor and trailer manufacturers

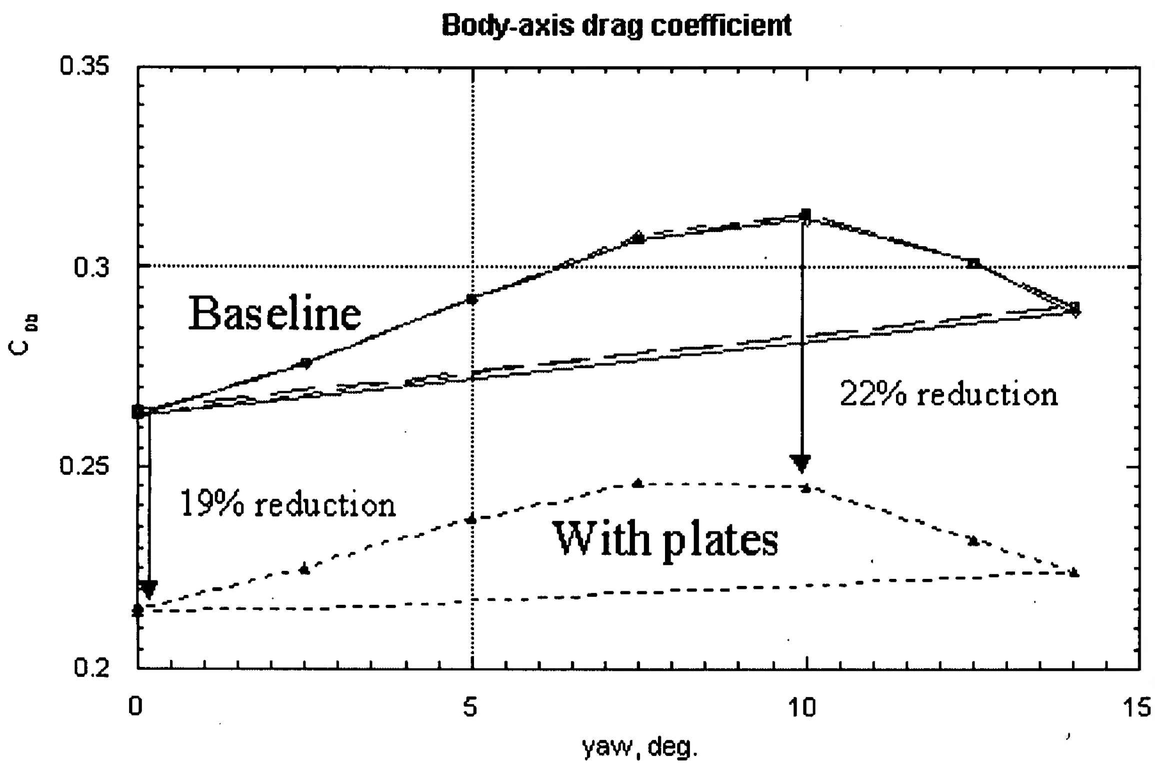
The effects of design changes on drag are not well understood and computational guidance is needed

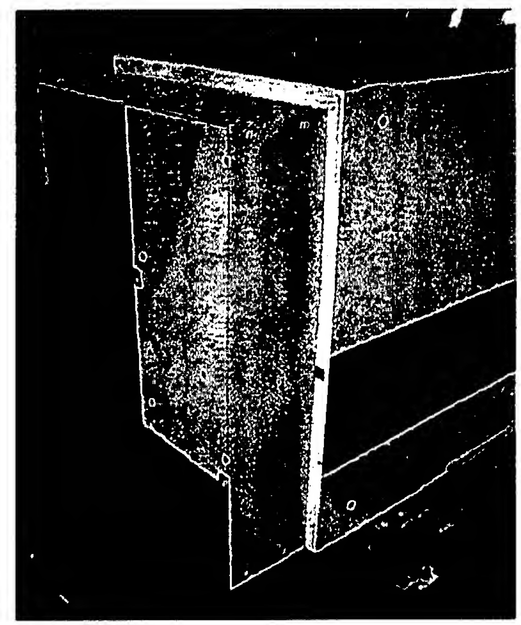
It is possible to realize a 10 to 15% savings in fuel consumption by reducing the drag coefficient by one-quarter.

Example

Boattail plates reduce base drag (wake reduction)

- **> 20% reduction in wind tunnel on simple model**
- **~ 10% reduction on real truck**





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Objectives

Develop aerodynamically optimized vehicles which will reduce drag coefficients by

2 - 5%	**Near Term**
4 - 10%	**Mid Term**
5 - 25%	**Far Term**

which will reduce the vehicle fuel consumption by

0.8 - 3%	**Near Term**
1.6 - 6%	**Mid Term**
2 - 15%	**Far Term**

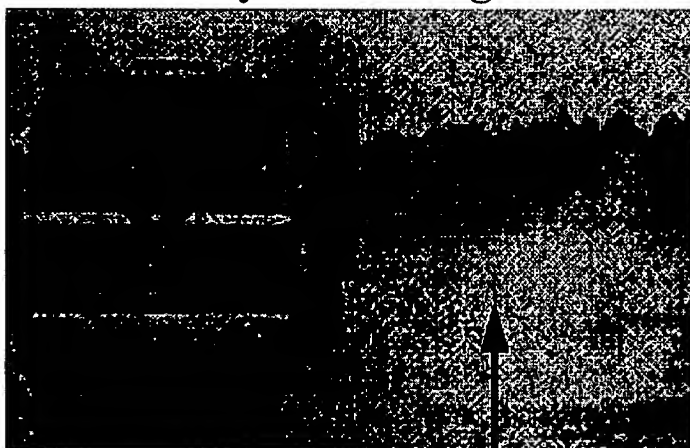
It is possible to realize a 10 to 15% savings in fuel consumption by reducing the drag coefficient by one-quarter.

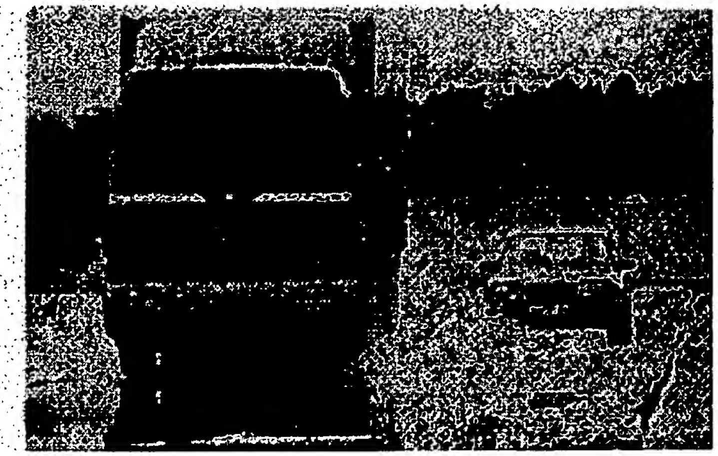
Percent Improvement in Drag Coefficient

Vehicle Class/Type	Near Term		Mid Term		Far Term	
	Conservative	Aggressive	Conservative	Aggressive	Conservative	Aggressive
2/Utility Truck	2	5	4	10	10	20
6/Enclosed Delivery Truck	<2	<5	<4	<10	5	15
7/Refuse Hauler	<2	<5	<4	<10	5	15
8/Line Haul Rig	2	5	4	10	10	25
8/Dump Truck	<2	<5	<4	<10	5	15

Improve truck safety by reducing the effects of splash and spray and lateral wind loads.

Efficient aerodynamic design leads to less spray

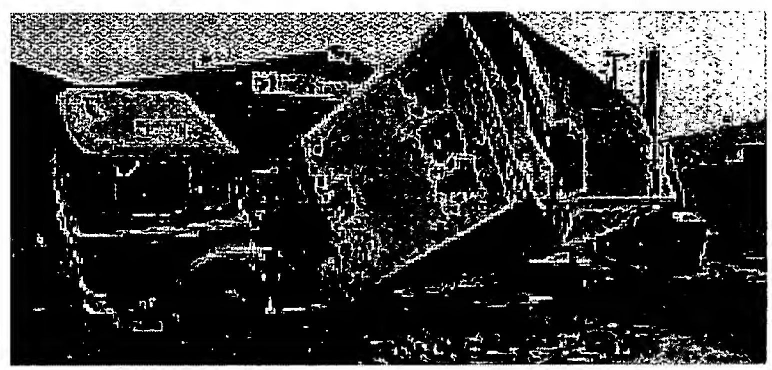




Car disappears behind water spray

1993 Annual Review of Fluid Mechanics
Photos Courtesy of Mercedes-Benz

The large lateral surface area of trucks results in considerable aerodynamic forces for yawed wind loads.



Splash and Spray: Large uptakes of water from the truck tires pose a safety issue.

Goal: Understand mechanisms causing water uptake and spray and determine methods of mitigation

Formulate design rules for the minimization of tire and vehicle spray

Approach: Computational and experimental studies of water spray and splash

Baseline experimental studies - establish fundamental mechanisms

Development of computational tools for water sheet and spay simulation

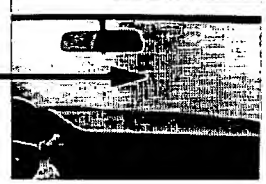
Laboratory experiments for code validation

Develop guidelines for spray mitigation

Standard Mudguard

Car not visible

Truck not visible to driver



Grooved Mudguard

Reduced water flow between tire and mudguard

Truck and car can be seen clearly

Ref. SAE paper 950631

Thermal management: Allow for flexibility of hood and truck design for minimizing drag.

Goal: **Improve internal flows for minimum drag and maximum thermal transport**

Radiator positioning and design

Improved hood/truck shapes

Approach: **Use of computational tools with experimental verification to model underhood flow**

Development of coupled flow/thermal transport computational tools

Perform laboratory experiments for code validation

Investigate innovative underhood configurations

DOE Project: Enabling industry to reduce aerodynamic drag on Class 8 trucks.

Goal: **Reduce fuel consumption and lower emissions of heavy trucks by reducing aerodynamic drag**

Focus: **Development and demonstration of a simulation capability**

Computations: **Computational design capability and**

Making wind tunnel testing more effective

- Steady, time averaged RANS modeling (SNL)

- Unsteady, 3-dimensional LES modeling (LLNL and Caltech)

Experiments: **Insight into drag effects**

Database for code validation

- High speed wind tunnel testing (NASA)

- Investigation of tractor-trailer height mismatch and gaps (USC)

- Past baseline case for code validation at low speeds (SNL/Texas A&M)

The DOE program has assembled a team of experts and established a working relation with industry.

Industry ⟷ **Military**

Rose McCallen (LLNL), Program Lead

Experimental Modeling

Jim Ross
Bruce Storms, JT Heineck

National Aeronautics & Space Administration

High Speed Experiments in 7'x10' Wind Tunnel

Fred Browand
Mustapha Hammache

USC University of Southern California

Moderate Speed Experiments in Wind Tunnel

Bob Englar

Georgia Tech Research Institute

Active Systems

Computational Modeling

Rose McCallen, Dan Flowers, Tim Dunn

University of California Lawrence Livermore National Laboratory

Large-Eddy Simulation using Finite Element Methods

Anthony Leonard
Mark Brady

Caltech California Institute of Technology

Large-Eddy Simulation using Vortex Methods

Kambiz Salari
Walt Rutledge

Sandia National Laboratories

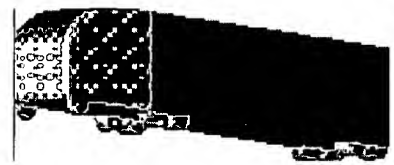
Reynolds-Averaged and Detached-Eddy Simulations using Finite Volume Methods

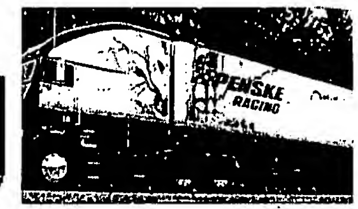
Aerodynamic Design

Accomplishments: The team of experts is established and significant progress has been made.

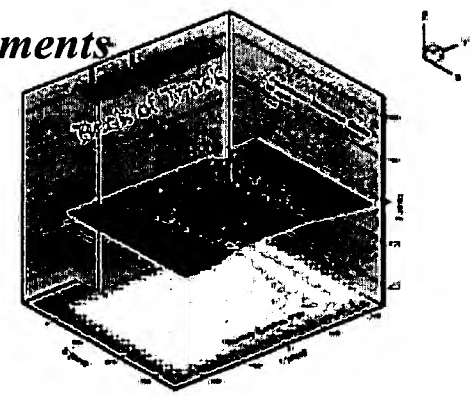
- Established multi-lab, multi-university team
- Working relation with industry
- Multi-year program plan in place
- Experiments completed for baseline case (first time 3D, unsteady velocity field measured in a production wind tunnel)
- Preliminary RANS calculations generated
- Advanced model development and computations in progress

Baseline case





Experiments



Computations